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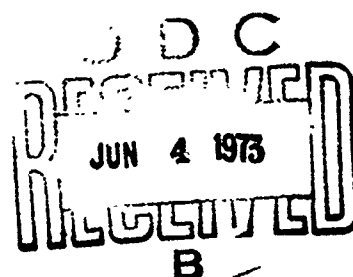
# QUANTITATIVE EVALUATION OF SMOKE ABATEMENT SYSTEM FOR CRASH/RESCUE TRAINING FIRES

James T. Haney  
Capt, USAF, BSC

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University of New Mexico, CERF

TECHNICAL REPORT NO. AFWL-TR-73-106

May 1973



AIR FORCE WEAPONS LABORATORY

Air Force Systems Command

Kirtland Air Force Base

New Mexico

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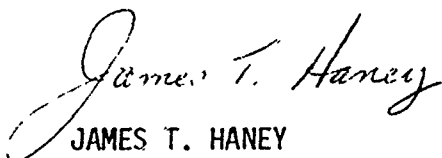
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FOREWORD

This report was prepared by the Air Force Weapons Laboratory and the Eric H. Wang Civil Engineering Research Facility, University of New Mexico, Albuquerque, New Mexico, under Contract F29601-72-C-0024. The research was performed under Program Element 63723F, Project 683M, Subtask 3A02.

Inclusive dates of research were 4 August 1972 through 28 February 1973. The report was submitted 19 April 1973 by the Air Force Weapons Laboratory Project Officer, Captain James T. Haney (DEE).

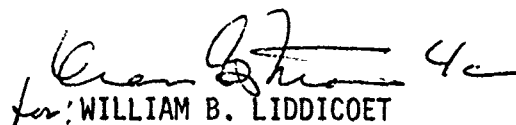
This technical report has been reviewed and is approved.



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ABSTRACT

(Distribution Limitation Statement B)

The training of Air Force firefighting personnel involves the extinguishing of large fires that simulate aircraft crash situations. Such fires generate clouds of thick black smoke that are objectionable from an air pollution viewpoint and, therefore, cannot be continued on the present basis. This report outlines the quantitative evaluation of the water spray injection smoke abatement system for the training fires. Basic design criteria have been established for the smoke abatement systems and emission factors in terms of pounds of particulates per 1000 pounds of fuel were determined for JP-4 fires.



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## SECTION I

## INTRODUCTION

The training of Air Force firefighting personnel involves the extinguishment of large fires that simulate aircraft crash situations. A training simulator consists of a full-scale mockup of an aircraft in the center of an area over which aircraft fuel is spilled and ignited. The trainees are instructed in the extinguishment of the fire and in the rescue of personnel from the fuselage of the aircraft. Such fires generate very large clouds of thick black smoke that are objectionable from an air pollution viewpoint. A process was developed by the Navy whereby fires from the free surface of No. 2 fuel oil can be treated to eliminate smoke generation (ref. 1). This treatment consisted of injecting an atomized water spray near the surface of the burning oil. The effectiveness of this smoke abatement process was indicated by analyses that were made on samples of the combustion products taken 20 feet above a 4- by 4-foot model used in the development work (table I). Not only was the generation of particulates reduced to a point where there was practically no visible smoke emission, but the emission of some invisible polluting gases also was reduced, and none increased.

There are some basic differences between Navy and Air Force firefighting training, and the major ones that concern the use of this Smoke Abatement Process pertain to the type of fuel and the method of burning. The Navy uses mostly No. 2 fuel oil while the Air Force uses JP-4, which is much more volatile (table II). In Navy simulators, the fuel oil is floated atop a relatively thick sub-layer of water, while the Air Force mockups involve fuel spills directly on the ground.

The present program was undertaken by the Air Force Weapons Laboratory (AFWL) to quantitatively investigate the efficiencies of the water spray injection process for smoke abatement on JP-4 fires and to provide basic design criteria for the installation of smoke abatement systems Air Force wide.

Table 1  
ANALYSES OF STACK GASES (ref. 1)

Measured Emissions	Open Tank					Tank with Side Walls				
	Treatment (lb/min-ft <sup>2</sup> )					Treatment (lb/min-ft <sup>2</sup> )				
	Optimum	Optimum Minus 0.05	Optimum Minus 0.10	Optimum Minus 0.15	None	Optimum	Optimum Minus 0.05	Optimum Minus 0.10	Optimum Minus 0.15	None
Solids (μg/ft <sup>3</sup> )	0.475	0.425	0.375	0.325	0.2	0.525	0.475	0.425	0.375	0.3
SO <sub>3</sub> (ppm)	1330	3400	3910	6760	27,000	562	4190	15,250	50,000	50,000
SO <sub>2</sub> (ppm)	5.8	3.2	7.3	4.6	13.2	1.9	7.9	9.2	11.1	13.8
NO <sub>x</sub> (ppm)	2.3	6.3	4.5	8.3	5.1	0.2	4.2	4.0	5.5	6.8
	0.47	0.81	0.91	0.95	0.81	0.19	0.74	0.52	0.59	0.35
Methane, CH <sub>4</sub> (ppm)	3.4	0.9	1.6	1.7	8.3	3.0	6.0	6.6	14.2	17.3
Ethane, C <sub>2</sub> H <sub>6</sub> (ppm)	0.2	0.2	< 0.03	< 0.03	0.2	0.1	0.1	0.1	0.1	0.2
Ethylene, C <sub>2</sub> H <sub>4</sub> (ppm)	3.5	1.8	2.5	3.5	9.0	1.2	3.7	4.5	8.6	6.4
Propane, C <sub>3</sub> H <sub>8</sub> (ppm)	0.7	0.6	0.5	0.7	0.6	0.7	0.7	0.7	0.8	0.6
Propylene, C <sub>3</sub> H <sub>6</sub> (ppm)	0.6	0.2	0.4	0.3	1.1	0.7	0.7	0.7	0.8	0.6
Isobutane, i-C <sub>4</sub> H <sub>10</sub> (ppm)	0.2	0.2	0.2	0.4	0.6	0.1	0.3	0.2	0.2	0.2
n-Butane, n-C <sub>4</sub> H <sub>10</sub> (ppm)	0.3	0.3	0.4	0.4	0.6	0.1	0.3	0.2	0.2	0.2
Isopentane, i-C <sub>5</sub> H <sub>12</sub> (ppm)	< 0.1	0.2	< 0.1	< 0.1	0.4	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
n-Pentane, n-C <sub>5</sub> H <sub>12</sub> (ppm)	< 0.1	0.2	< 0.1	< 0.1	0.2	< 0.1	0.2	< 0.1	< 0.1	< 0.1
C <sub>6</sub> Family (ppm)	0.8	0.4	0.2	0.4	2.3	1.3	4.7	0.8	1.4	1.5
Oxygen O <sub>2</sub> (%)	20.3	19.4	17.6	19.1	18.6	19.7	18.2	18.6	17.9	18.9
Carbon Dioxide, CO <sub>2</sub> (%)	0.4	1.1	1.7	1.1	1.7	1.0	1.8	1.6	2.1	1.3
Carbon Monoxide, CO (%)	< 0.01	< 0.01	0.01	0.01	0.02	< 0.01	0.01	0.01	0.02	0.02

Table II

TYPICAL CHEMICAL AND PHYSICAL CHARACTERISTICS  
OF NO. 2 FUEL OIL AND AVIATION GRADE TURBINE FUEL (JP-4)

Property	No. 2 Oil	JP-4
Flash Point (°F)	151	-70
Pour Point (°F)	-10	-70
Distillation (90% Recovery)	599	439
Gravity (DEG API)	34	53
Sulfur, Wt (%)	0.25	0.09
Aromatics, Wt (%)	50	12.9
Olefins, Wt (%)	---	1.1

## SECTION II

### EXPERIMENTAL

#### 1. EQUIPMENT

The laboratory model used for the experiments described in this report consists of a 4- by 4-foot tank which is located near floor level below an 8- by 8-foot stack.

A 4- by 4-foot fire area is sufficiently large to provide fully developed turbulent burning (ref. 2), and consequently the fire behavior should be representative of much larger fires. The pan was constructed using heavy gauge metal with pipe connections as shown in figure 1. An 8-inch bed of 1/2-inch gravel was placed in the pan. The height of the fuel was maintained at the surface of the gravel layer by controlling the height of a liquid level using overflow pipes. An overhead view and cross section of the pan appears in figure 2.

To aid in sampling the fire, an 8- by 8-foot tower--21 feet high as shown in figure 3--was erected. The fire pan was placed at the bottom of the tower and sampling was done at the 20-foot level using scaffolding placed beside the tower. A stack sampler obtained from McClellan AFB was used for the particulate determination as well as  $\text{SO}_2$ - $\text{SO}_3$ . The use of this equipment is well documented by Air Force technical reports (ref. 3). Grab samples were also taken at the 20-foot level by using Mylar bags placed in an evacuated box.

A Lira Analyzer Model 200 and a Beckman 6800 Air Quality Chromatograph were located in a shelter near the sampling tower, and a 1/4-inch Teflon tube was run from the sampling probe to the analysis equipment. The sampling pump, which is built into the Beckman 6800, was used to draw a continuous sample from the fire. This allowed the CO concentration to be continuously monitored and the total hydrocarbon to be determined every 45 seconds.

The total particulate loading was determined by measuring the amount of particulate matter collected for a known volume of gas sampled. The grab samples which were obtained during the runs were taken to the laboratory to be

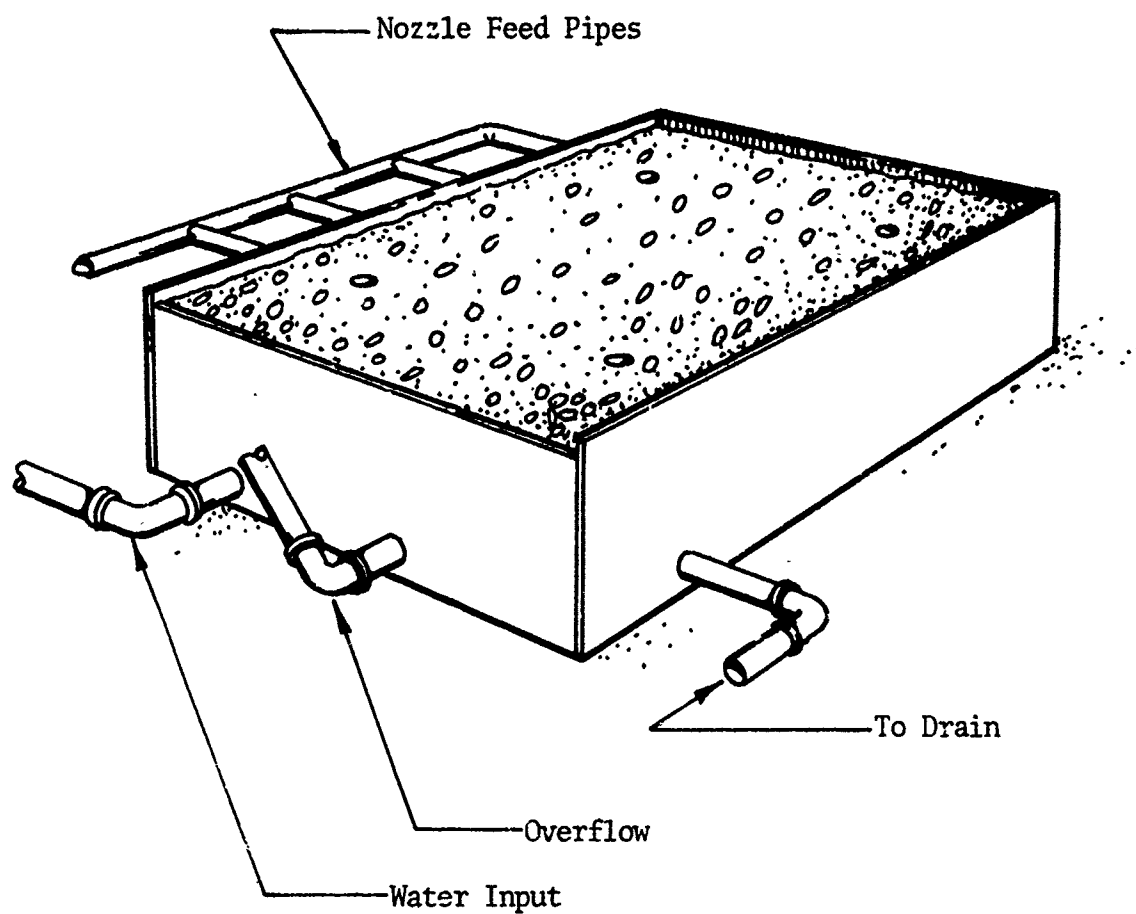


Figure 1. Schematic Diagram of Fire Pan

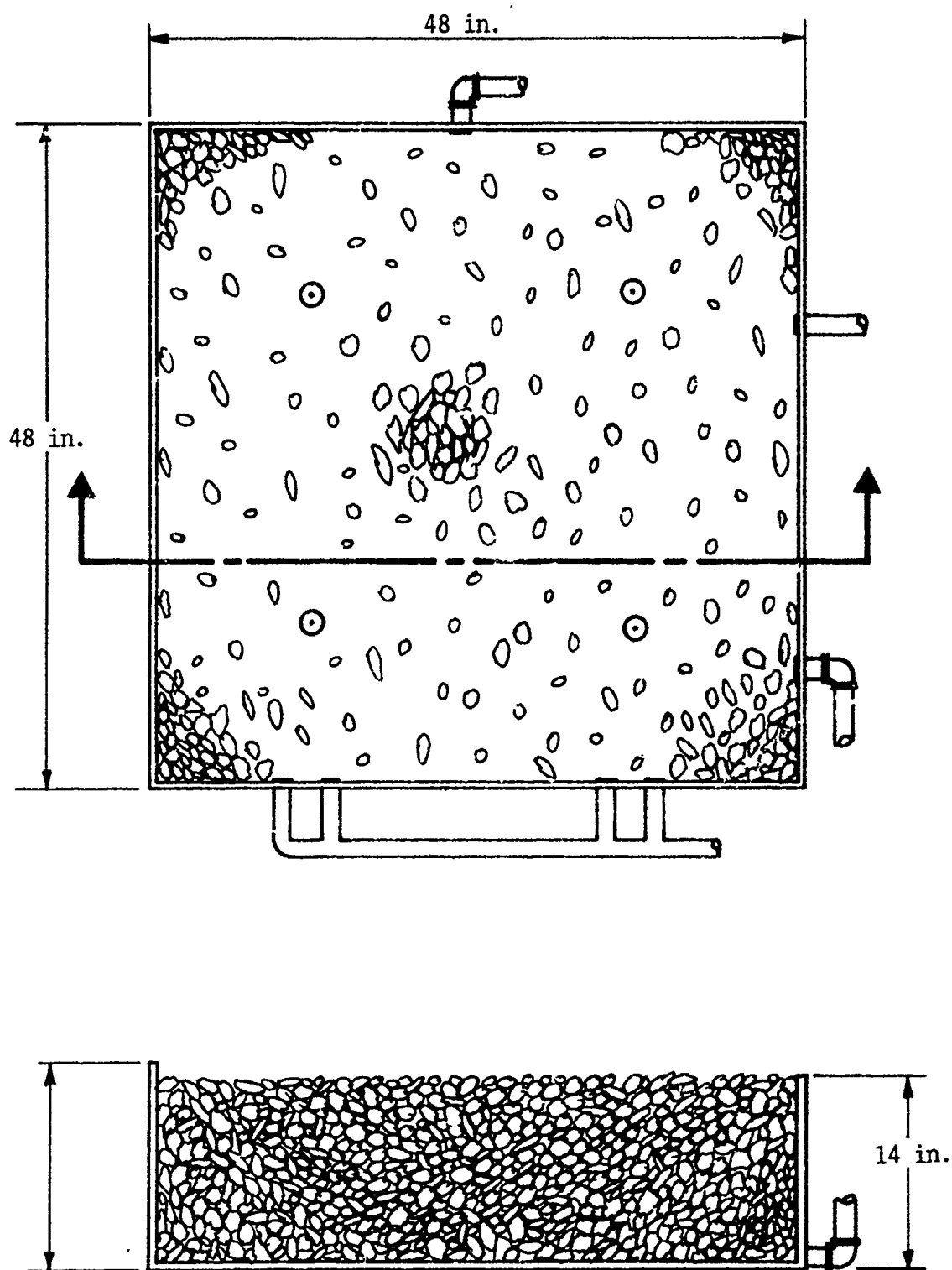


Figure 2. Overhead View and Cross Section of Fire Pan



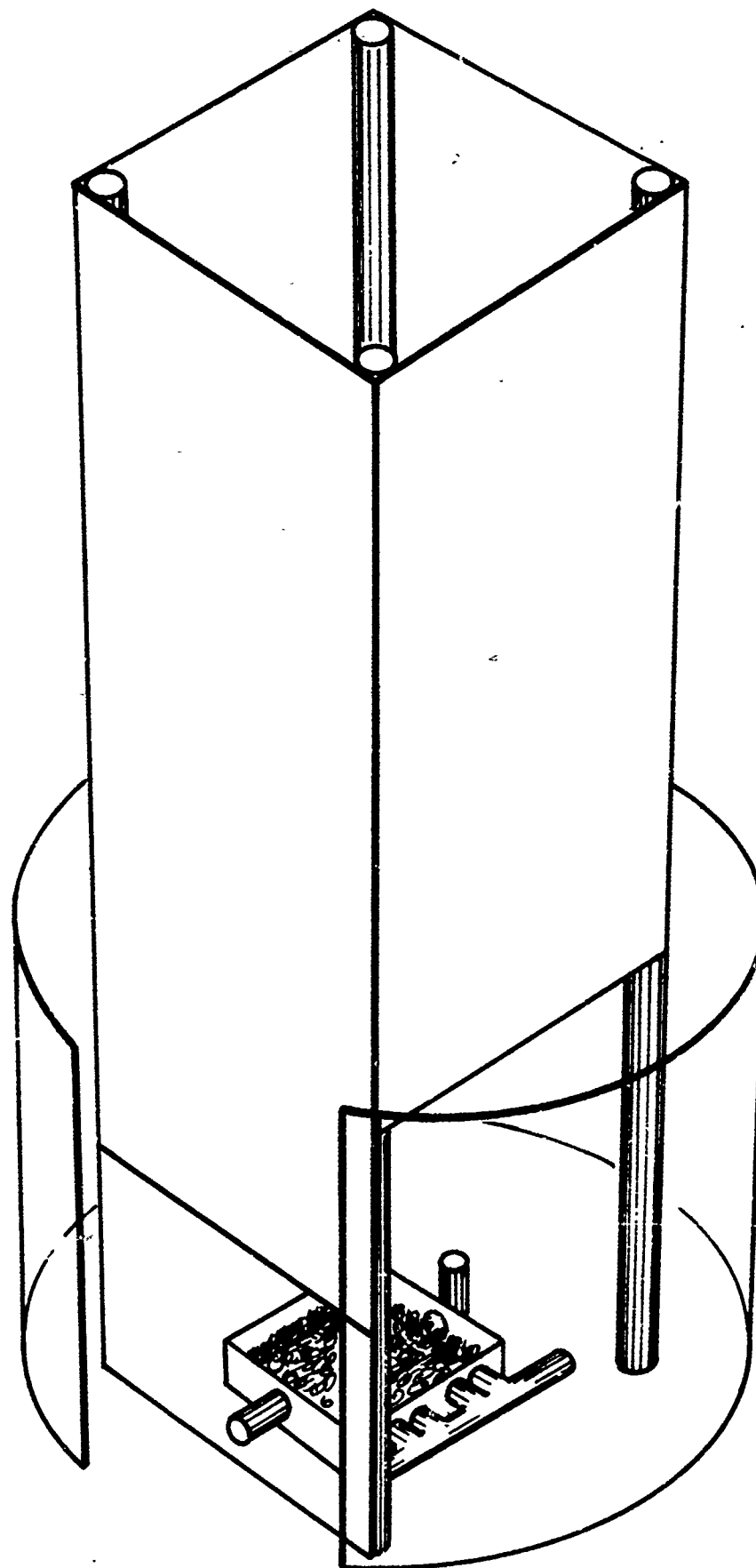


Figure 3. Exhaust Stack and Sampling Location

analyzed for total aliphatic aldehydes, by the 3-methyl 2-benzothiazolone hydrazone hydrochloride (MBTH) method (ref. 4),  $\text{NO}_x$  using the phenoldisulfonic acid method (ref. 5) and  $\text{C}_1\text{-C}_6$  by gas chromatography.  $\text{SO}_2$  and  $\text{SO}_3$  concentrations were determined by Seidman method (ref. 6). Benzo (a) pyrene determinations on the carbon particles were performed using liquid chromatography (ref. 7).

Three different nozzles were used for the testing and were arranged in two different configurations. The nozzles which were used are listed below.

1/8-inch Deflectojet*	0.375 gpm at 40 psi	4 used
1/4-inch Deflectojet*	1.5 gpm at 20 psi	1 used
1/4-inch Parasol*	1.0 gpm at 20 psi	1 used

The four-nozzle system was arranged as shown in figure 2. When using a single nozzle, it was placed in the center of the pan. The heights of the nozzles were adjusted so that they were approximately 1/2-inch above the liquid surface.

## 2. PROCEDURE

The equipment for continuous monitoring was allowed to warm up overnight to stabilize before the analysis. A weighted filter and cyclone trap were placed in the sample train along with reagents for  $\text{SO}_2\text{-SO}_3$  analysis. A Mylar bag was placed in the sample box and lines connected to the vacuum pump.

Ten gallons of fuel were then added to the fire pan and the water level adjusted to approximately 1/4-inch below the level of the gravel by using the overflow pipe. The fuel was then ignited. On each test day at least one untreated JP-4 fire was burned for comparison. The amount of water spray added to the fire was controlled by adjusting the water pressure applied to the nozzle (figure 4).

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\*Manufactured by the Spraying System Co., Bellwood, Illinois 60104.

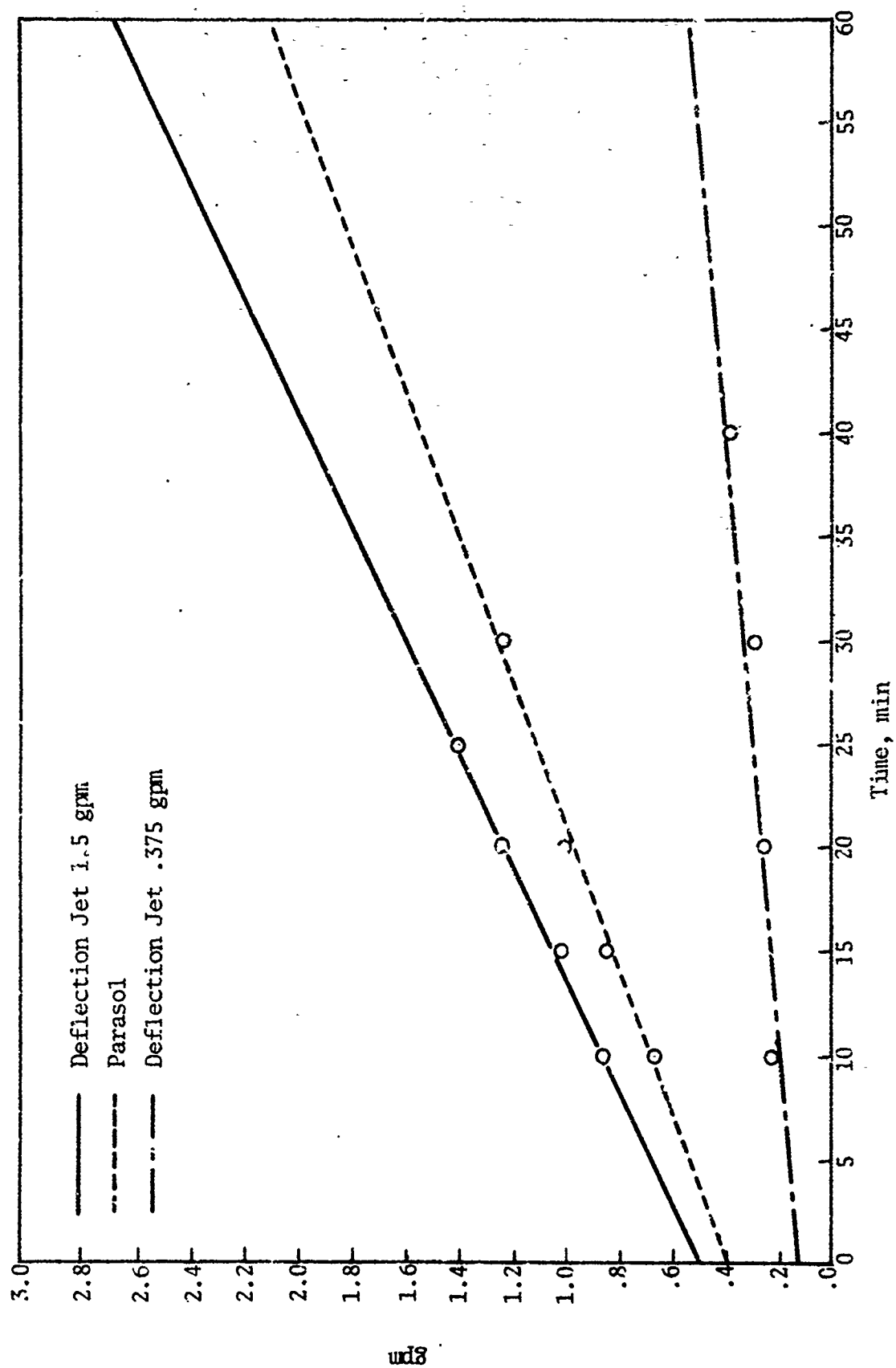


Figure 4. Flow Calibration for Spray Nozzle

### SECTION III

#### RESULTS AND DISCUSSION

The results for all the fires are presented in table III. Several No. 2 fuel oil fires were also sampled in the test apparatus and the data compared with the work previously performed by Illinois Institute and Technology Research Institute (IITRI) under a Navy contract. A large variation between AFWL and IITRI data is noted for the particulate loadings on the untreated diesel oil fires (table IV). Further investigation into the possible reason for such a large variation revealed differences in the conditions under which the work at IITRI and AFWL was performed.

The major differences are

	<u>IITRI</u>	<u>AFWL</u>
1. Quantity of fuel	25 gallons	10 gallons
2. Test bed substratum	water	water and gravel
3. Sampling system	ceramic filter	glass fiber filter
4. Sampling tower design	restricted top	unrestricted
5. Test bed location	enclosed building	outside

During each of the IITRI tests, a quantity of 25 gallons of No. 2 fuel oil was burned on a water substratum. Only 10 gallons of fuel oil were used in the AFWL fires, and the burning was on a water and gravel substratum. However, these differences have been found to have no significant effect on the burning characteristics of a fire of constant area (ref. 8). IITRI utilized a ceramic filter system for collection of the particulates whereas AFWL used a cyclone and glass fiber filter arrangement. The difficulty in the technique of using the ceramic filter could account for only a 20- to 30-percent error in the particulate loadings (ref. 9).

The basic design of the test bed was the same in both installations. Both were 4- by 4-foot test beds located underneath 8- by 8-foot sampling towers. The IITRI tower and test bed were located inside a large building and were vented

Table III  
DATA OBTAINED FROM TREATED AND UNTREATED OPEN BURNING JP-4 FIRES

Treatment	Application Rate (lb H <sub>2</sub> O/ft <sup>2</sup> min)	Particulate Loading (STP) ( $\mu\text{g}/\text{ft}^3$ )	NO <sub>2</sub> (ppm)	Aldehyde (ppm)	Temp (°F)
Untreated	N/A	6200	4.52	1.21	1480
Deflectojet Nozzle 4 (1/8 inch)	1.05	1590	---	---	---
Untreated	N/A	6260	---	---	---
Deflectojet Nozzle 1 (1/4 inch)	1.20	1420	---	---	---
Untreated	N/A	5500	---	---	---
Deflectojet Nozzle 1 (1/4 inch)	1.40	1955	2.39	1.13	1260
Untreated	N/A	6500	---	---	---
Parasol Nozzle 1 (1/4 inch)	0.75	940	0.05	0.75	---
Untreated	N/A	7720	---	---	---
Parasol Nozzle 1 (1/4 inch)	1.0	820	0.01	0.62	---
Untreated	N/A	7720	---	---	---

Table IV  
COMPARISON OF PARTICULATE EMISSIONS  
FROM 4- x 4-FOOT NO. 2 FUEL OIL FIRES

Fuel	Particulate Loadings ( $\mu\text{g}/\text{ft}^3$ )	Performing Lab
No. 2 Fuel Oil	9,200	AFWL
No. 2 Fuel Oil	9,670	AFWL
No. 2 Fuel Oil*	21,000	AFWL
No. 2 Fuel Oil	27,000	IITRI

\*After restricting flow out the top of the sampling tower as was done with the IITRI apparatus.

out the roof. The AFWL System was located on the outside and was protected from the wind by a baffle arrangement which was positioned so as not to restrict the air supply to the fire. Also, the IITRI sampling tower was restricted at the top to aid in the sampling of the plume. The AFWL tower was in no way restricted.

It could not be estimated how much the particulate loadings could be affected by the restriction inherent in the IITRI system. Therefore, the AFWL tower was modified to incorporate the restricted top. This resulted in an increased particulate loading from  $9000 \mu\text{g}/\text{ft}^3$  to  $21,000 \mu\text{g}/\text{ft}^3$  which compares favorably with the  $27,000 \mu\text{g}/\text{ft}^3$  for the fires burned in the IITRI laboratory. Thus, it can be deduced that fires burned in the AFWL testing apparatus are more indicative of "open, free-burning" fires than were those studied by IITRI.

The Environmental Health Laboratory at McClellan AFB performed a study in November 1971 of the air pollutant emission from JP-4 fires used in firefighting training (ref. 10). Their sampling was conducted in the engine room simulator at the Fire Training Facility at Treasure Island Naval Station. The Naval Station has an afterburner emission control system to which combustion products from training fires in the enclosed engine room simulator are ducted. JP-4 was burned in the facility and the ducts samples to determine the combustion products

of the fire. Table V shows the pollutant concentrations as determined by the McClellan Environment Health Laboratory. The particulate concentration of 59,000  $\mu\text{g}/\text{ft}^3$  agrees well with the loadings determined by IITRI for a No. 2 fuel oil burning in a tank with side walls (to restrict air supply).

Table V  
POLLUTANT CONCENTRATIONS FOR JP-4 FIRES REPORTED BY  
McCLELLAN ENVIRONMENTAL HEALTH LABORATORIES (ref. 10)

Solid Particulates	59,000 $\mu\text{g}/\text{SCF}$
Carbon Dioxide	2.03 percent
Carbon Monoxide	2720 ppm
Methane	687 ppm
Ethylene	388 ppm
Acetylene	130 ppm
Formaldehyde	5174 $\mu\text{g}/\text{SCF}$

Figure 5 depicts the carbon monoxide (CO) and total hydrocarbon (THC) concentration for an untreated JP-4 fire as determined by AFWL. Both instruments, the Lira Model 200, and the Beckman 6800 were driven off scale at the lowest sensitivity settings for the instrument, so that peak emissions could not be determined for the untreated case.

Initially, AFWL smoke abatement studies were made using a four-nozzle spray pattern with 1/8-inch Deflectojet nozzles at a water deposition rate of 1.1 lb/ft<sup>2</sup>-min. Although the particulate loading was reduced from 6,500  $\mu\text{g}/\text{ft}^3$  to 1,500  $\mu\text{g}/\text{ft}^3$  there was still a noticeable amount of black smoke given off. The continuously recorded concentration of CO and THC are shown in figure 6. There was a definite decrease in CO concentration and the THC concentration shows a measurable decrease earlier in the burn time. However, the burn time for a treated fire is approximately 2 minutes greater than an untreated fire. This would indicate the water spray injection system reduces the rate of vaporization of the fuel.

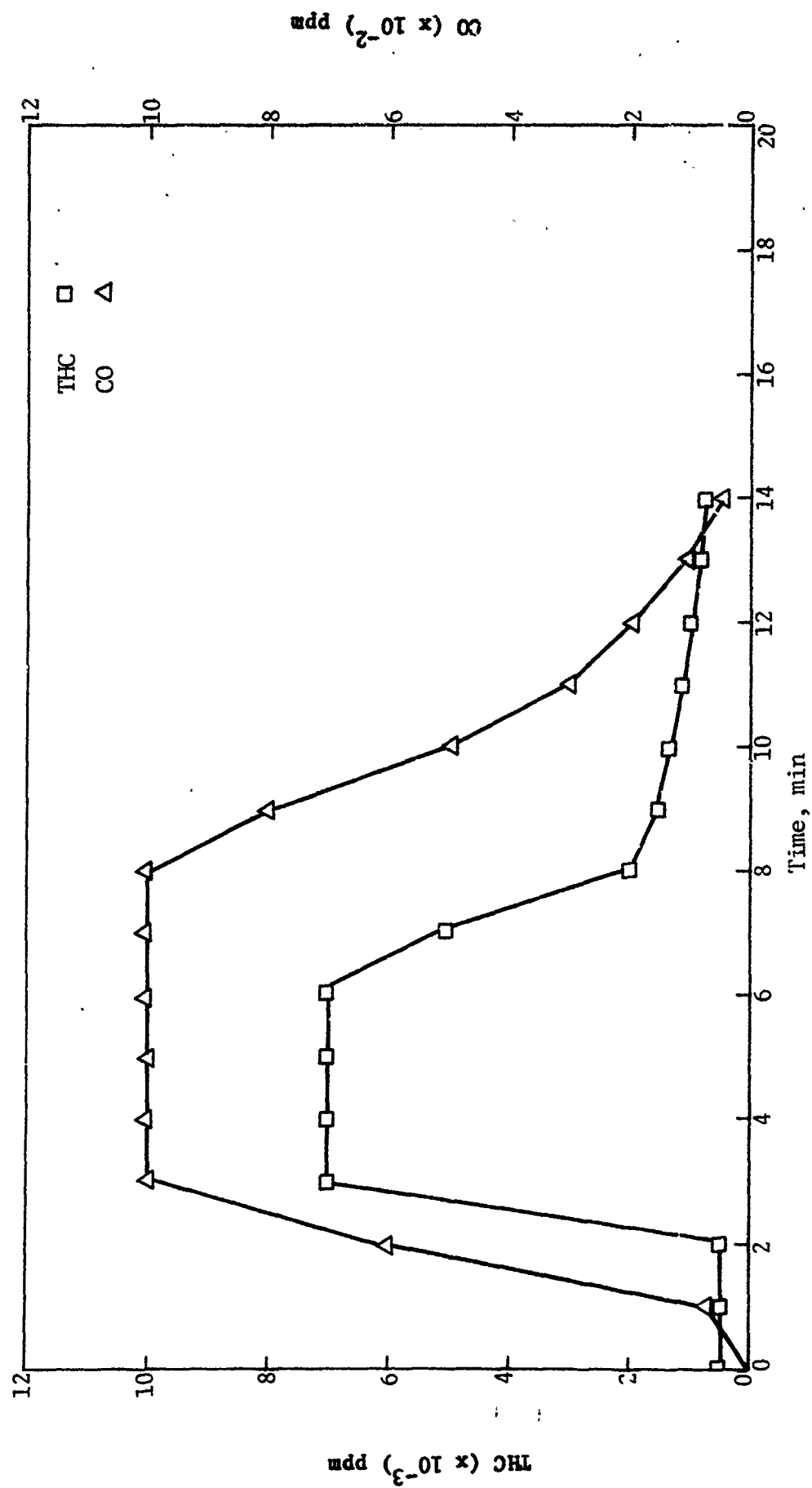


Figure 5. Continuously Monitored CO and THC Concentration for an Untreated JP-4 Fire



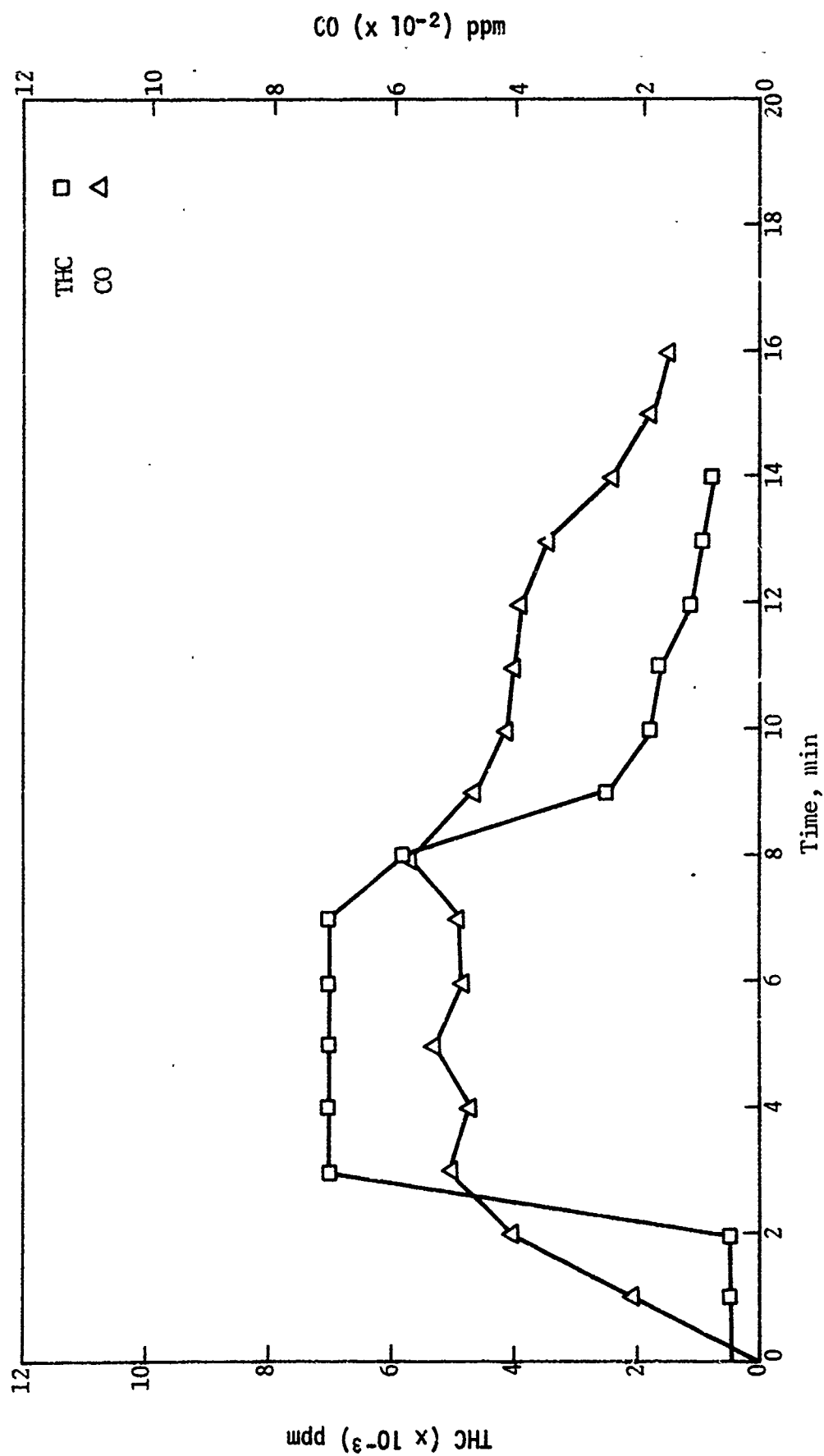


Figure 6. Continuously Monitored CO and THC Concentration for a JP-4 Fire Treated with Four Nozzles at 1.1 lb/ft<sup>2</sup>/min H<sub>2</sub>O

To decrease the particulate emissions a larger nozzle was used and the water application rate increased. With the water application rate increased to 1.4 lb/ft<sup>2</sup>-min no noticeable improvement in the concentration of pollutants was evidenced. An examination of the data indicates that the particulate control was even worse than at the lower flow rates. Figure 7 shows that the CO concentration was higher than that for the four-nozzle system utilizing the 1/8-inch Deflectojet. It can be noted from table IV that the NO<sub>x</sub> concentration was decreased significantly and the total aldehyde concentration was decreased compared to an untreated fire.

Much better results were obtained using Parasol nozzles (figure 8). The spray pattern had a 160-degree spray angle and the degree of atomization was higher. From table IV it is evident that better particulate control was obtained even at a reduced water application rate. The NO<sub>x</sub> concentration was reduced drastically over the untreated fires and the total aldehyde concentration was halved. The recorded flame temperatures for the test with the Parasol nozzle are in error because the thermocouple was located 6 inches above the nozzle, and spray from the nozzle cooled the thermocouple. Figure 8 indicates a better control of the CO emission and an increase in burn time. It is apparent that the best pollutant control was achieved by using a finely atomized spray.

No measurable amounts of SO<sub>2</sub>, SO<sub>3</sub>, or benzo (a) pyrene were found in samples from the JP-4 fires.

Emission factors for the JP-4 fires were calculated as outlined in the appendix. The factors determined for the untreated and the treated fires are:

	<u>Untreated</u>	<u>Treated</u>
Particulates	$\frac{128 \text{ lb}}{1000 \text{ lb fuel}}$	$\frac{17.6 \text{ lb}}{1000 \text{ lb fuel}}$
NO <sub>x</sub> (as NO <sub>2</sub> )	$\frac{4.15 \text{ lb NO}_2}{1000 \text{ lb fuel}}$	$\frac{0.012 \text{ lb NO}_2}{1000 \text{ lb fuel}}$
CO	$\frac{>560 \text{ lb CO}}{1000 \text{ lb fuel}}$	$\frac{284 \text{ lb CO}}{1000 \text{ lb fuel}}$

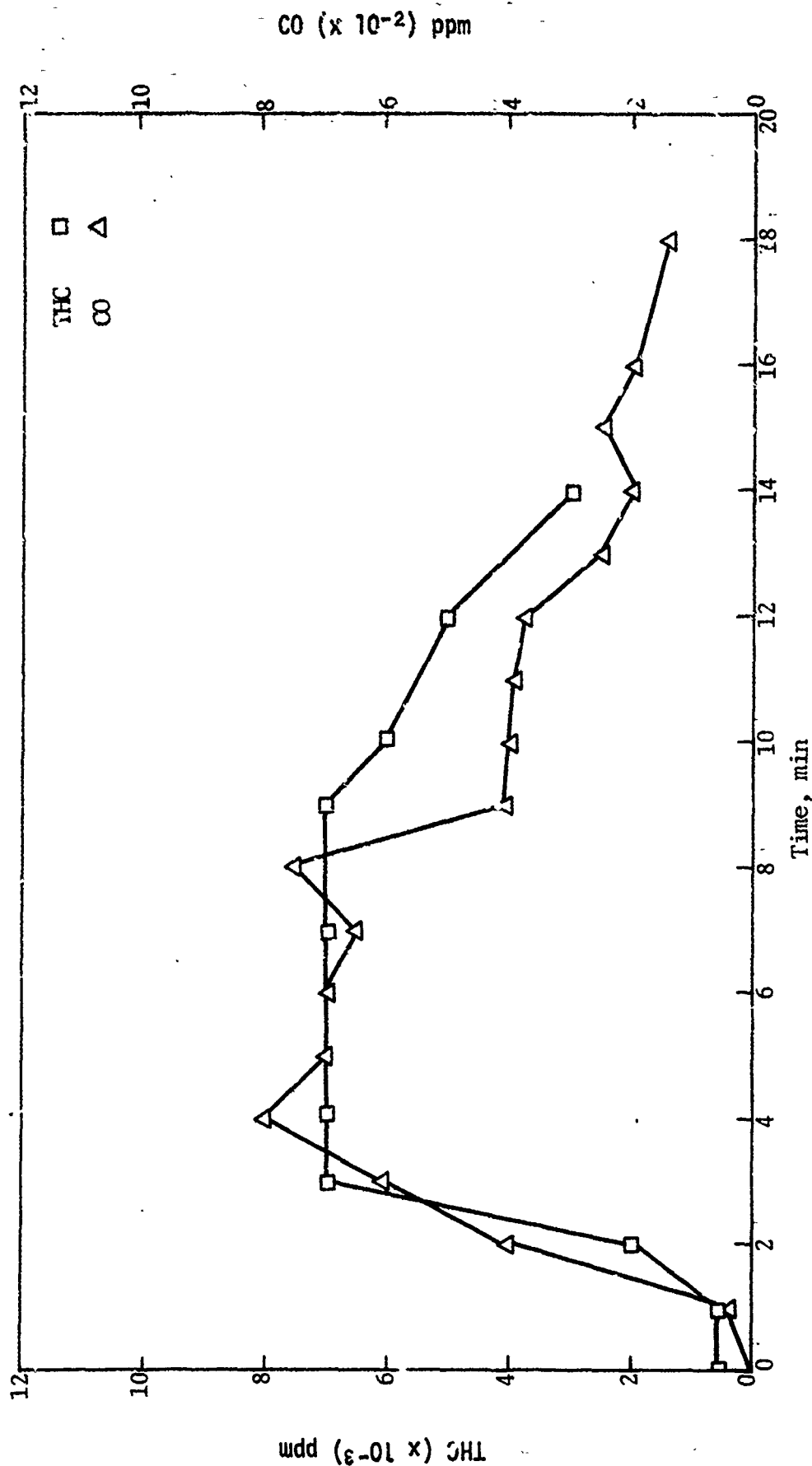


Figure 7. Continuously Monitored CO and THC Concentration for a JP-4 Fire Treated with One Deflectojet Nozzle at 1.4 lb/ft<sup>2</sup>/min H<sub>2</sub>O

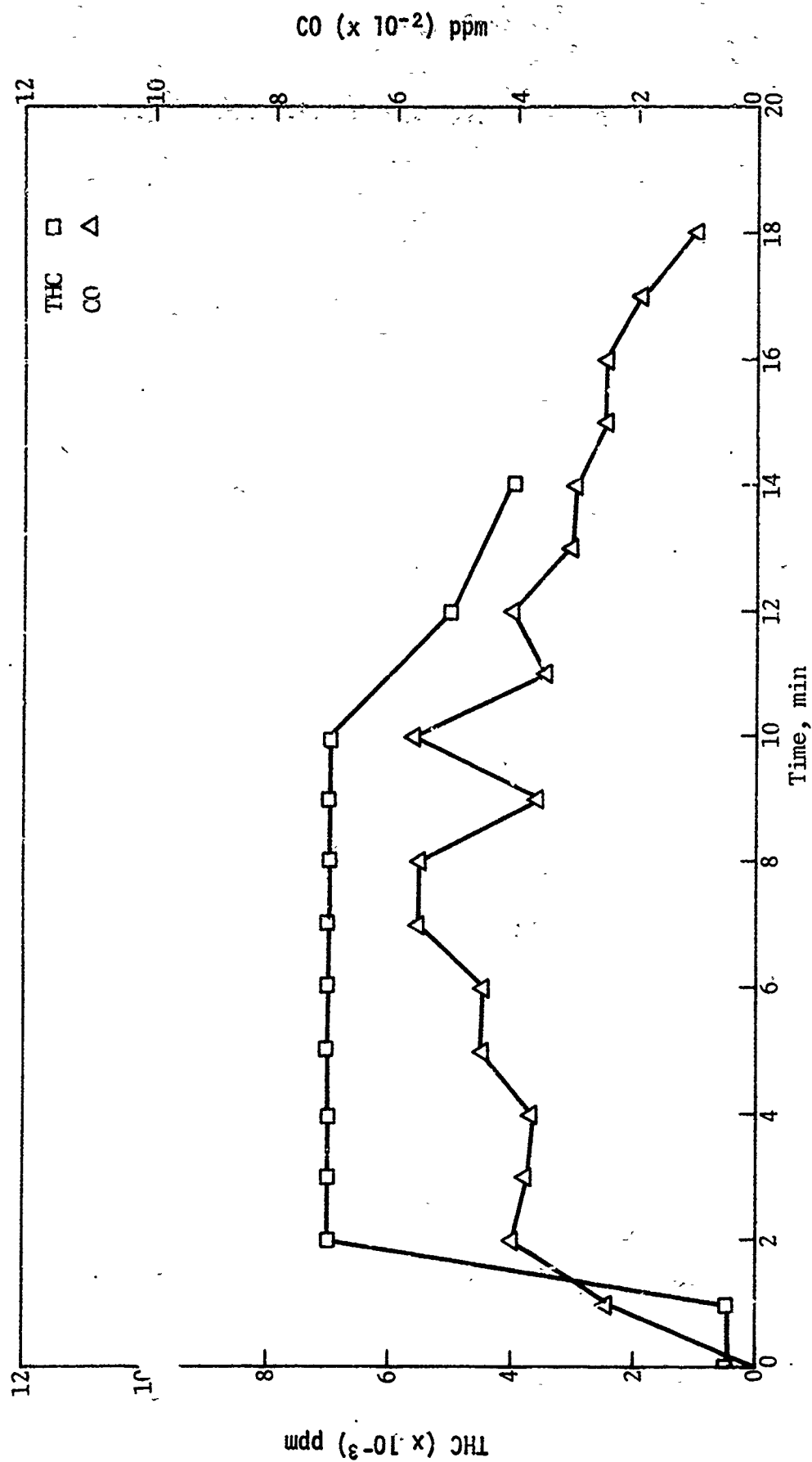


Figure 8. Continuously Monitored CO and THC Concentration for a JP-4 Fire Treated with One Parasol Nozzle at 0.75 lb/ft<sup>2</sup>/min H<sub>2</sub>O

SECTION IV.

CONCLUSIONS

1. Significant reductions in all emission from JP-4 fires can be obtained by the utilization of the water spray injection system.
2. JP-4 fires treated with water deposition rates of 0.75 and 1.0 lb H<sub>2</sub>O/ft<sup>2</sup>-min using a highly atomizing nozzle produced flame heights in excess of 10 feet and with no visible emissions.
3. The reduction in emissions from a JP-4 fire using the water spray injection system appears to be a function of the cooling of the surface of the petroleum thus reducing the rate of vaporization of the fuel.
4. The ability of the water spray to reduce the emissions is a function of the water deposition rate and the degree of atomization.

# APPENDIX

## CALCULATION OF EMISSION FACTORS FOR JP-4 FIRES

### Assumptions:

1. Stack draft is converted to velocity.
2. No stack losses.
3. Uniform flow patterns across top of stack.

### Temperature 1/2-foot above fire surface:

Untreated: 1480°F

Treated: 1260°F

### Fire temperature peaks at about 35 inches above the surface of the fire (ref. 11):

Untreated: 1700°F

Treated: 1400°F

### Average temperatures:

Untreated: 1600°F

Treated: 1350°F

### Calculation of stack draft and velocity:

$$H_w = 12H \gamma_g / \gamma_w \quad (1)$$

where

$H_w$  = head in inches of water

$H = V^2 / 2g$

$V$  = velocity in ft/sec

$g$  = gravitational constant, 32.2 ft/sec<sup>2</sup>

$\gamma_g$  = sp. wt. of the gas flowing, lb/cu ft

$\gamma_w$  = sp. wt. of water, lb/cu ft at ambient temperature (62.4 lb/ft<sup>3</sup>)

Rearranging and substituting for H in equation (1):

$$H_w = 12(V^2/2g)\gamma g/\gamma_w$$

$$V^2 = \frac{H_w 2g\gamma_w}{12\gamma g}$$

Calculation of  $H_w$  (ref. 12)

Untreated:

$$H_w = 0.0108 \frac{\text{inches } H_2O}{\text{ft stack ht}} \times 21 \text{ ft stack}$$

$$H_w = 0.2268 \text{ inches } H_2O$$

Treated:

$$H_w = 0.0100 \frac{\text{inches } H_2O}{\text{ft stack ht}} \times 21 \text{ ft stack}$$

$$H_w = 0.2100 \text{ inches } H_2O$$

Calculation of velocity through this stack

$$V^2 = \frac{H_w 2g\gamma_w}{12\gamma g}$$

Untreated fire:

$$V^2 = \frac{(0.2268)(64.4)(62.4)}{12(0.015)}$$

$$\gamma g = 0.015 \text{ (ref. 12)}$$

$$\gamma w = 62.4$$

$$V^2 = 5063.4 \text{ ft}^2/\text{sec}^2$$

$$V = 71 \text{ ft/sec}$$

Treated fire:

$$V = 65 \text{ ft/sec}$$

Calculation of air flow rates

$$A = \text{area of top of stack} = 64 \text{ ft}^2$$

$$Q = VA$$

Untreated fire:

$$Q_u = (71 \text{ ft/sec})(64 \text{ ft}^2)$$

$$Q_u = 4544 \text{ ft}^3/\text{sec at temperature of } 1600^\circ\text{F}$$

$$Q_u = 272,640 \text{ ACFM}$$

Temperature correction to 60°F:

$$Q_u = (272,640) \left( \frac{520^\circ\text{F}}{2060^\circ\text{R}} \right)$$

$$Q_u = 68,822 \text{ SCFM}$$

Treated fire:

$$Q_t = 69,780 \text{ SCFM}$$

Since  $Q_t$  is approximately equal to  $Q_u$  we can use an average rate =  $\bar{Q}$

$$\bar{Q} = \frac{69,780 + 68,822}{2}$$

$$\bar{Q} = 69,301 \text{ ft}^3/\text{min}$$

Calculation of emission factor for particulates

Untreated JP-4 fire:

$$\begin{aligned} W_{pu} &= 7700 \text{ } \mu\text{g}/\text{ft}^3 \times 69,301 \text{ ft}^3/\text{min} \\ &= \text{mass flow of particulates} \end{aligned}$$

$$W_{pu} = 533.62 \text{ gm/min} = 1.17 \text{ lb/min}$$

Quantity of fuel used:

$$10 \text{ gals} = 63.9 \text{ lb}$$

Duration of burn: 7 min

$$\frac{1.17 \text{ lb particulates}}{\text{min}} \times 7 \text{ min} \times \frac{1}{63.9 \text{ lb/fuel}} = \frac{0.128 \text{ lb part.}}{\text{lb fuel}}$$

Untreated fire:

$$\text{Emission factor} = \frac{128 \text{ lb/particulates}}{1000 \text{ lb fuel}}$$



Treated fire:

$$W_{pu} \approx 0.125 \text{ lb/min}$$

Duration of burn: 9 min

Quantity of fuel: 63.9 lb

$$\text{Emission factor} = \frac{17.6 \text{ lb particulates}}{1000 \text{ lb fuel}}$$

Calculation of emission factor for  $\text{NO}_2$

Untreated fire:

Concentration of  $\text{NO}_2 = 4.52 \text{ ppm}$

$$V_{\text{NO}_2} = \text{Volume of } \text{NO}_2 \text{ per fire} = \frac{69,301 \text{ ft}^3}{\text{min}} \times 7 \text{ min} \times \frac{4.52}{10^6}$$

$$V_{\text{NO}_2} = 2.19 \text{ ft}^3 \text{ of } \text{NO}_2$$

Assuming ideal gas law applies:

$$PV = NRT$$

$$m_{\text{NO}_2} = \frac{MPV}{RT}$$

$T = 250^\circ\text{R} = \text{temperature}$

$P = 1 \text{ atmos.} = \text{total pressure}$

$M = 46 = \text{molecular weight}$

$R = 0.7302 \text{ atmos. ft}^3/\text{lb mole } ^\circ\text{R} = \text{gas law constant}$

$$m_{\text{NO}_2} = \frac{(46)(1)(2.19)}{(0.7302)(520)}$$

$$m_{\text{NO}_2} = 0.2653 \text{ lb } \text{NO}_2/\text{fire}$$

$$\text{NO}_2 \text{ emission factor for untreated fire} = \frac{4.15 \text{ lb } \text{NO}_2}{1000 \text{ lb JP-4}}$$

Treated fire:

$$\text{NO}_2 \text{ emission factor for treated fire} = 0.012 \text{ lb } \text{NO}_2/1000 \text{ lb JP-4}$$

## Calculation of emission factor for carbon monoxide

Untreated fire:

Peak concentration (figure 5) was greater than 1000 ppm

$$V_{CO} = \frac{69,301 \text{ ft}^3}{\text{min}} \times 7 \text{ min} \times \frac{1000 \text{ ppm}}{10^6}$$

$$V_{CO} = 485 \text{ ft}^3 \text{ CO/fire}$$

$$M_{CO} = \frac{(485)(28)(1)}{(0.7302)(520)} = 35 \text{ lb CO/fire}$$

$$\text{Emission factor} = \frac{>559 \text{ lb CO}}{1000 \text{ lb fuel}}$$

Treated fire:

$$\text{Emission factor} = \frac{284 \text{ lb CO}}{1000 \text{ lb fuel}}$$

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